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October 22, 1991

Dr. Alan Weinstein
Ocean Sciences Division
Office of Naval Research
800 N. Quincy Street
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Dear Alan,

Enclosed is the final report for our URI. We appreciate your support during the past five years and feel that it greatly improved our productivity.

Sincerely,

Mike

Michael C. Gregg

cc: Dr. Alan Brandt, ONR

MIXING TO MESOSCALE

Final Report

22 October 1991

1. INTRODUCTION/BACKGROUND

Before the Mixing to Mesoscale URI, work being done on various aspects of oceanic mixing had little or no coordination. Oceanic measurements were carried out piecemeal, with insufficient time to relate them to measurements at other times and places; numerical and laboratory studies simulating oceanic mixing processes did not address the crucial questions needed to interpret the oceanic measurements. Furthermore, conceptual and analytical models were not related to specific processes. Consequently, there was no way to test basic notions—such as most mixing occurs at oceanic boundaries, and vertical fluxes result from the mixed water moving along sloping isopycnal surfaces.

To improve this situation, we brought together two observationalists studying small scales (Gregg and Sanford), a laboratory experimentalist (Van Atta), a numerical modeler (Riley), and a theorist interested in the mesoscale (Rhines). Meetings during the first year improved our understanding of problems in the different aspects of mixing and defined much of the work to be done. Some research, however, was not anticipated early on.

During the last two years we have concentrated on completing and publishing our initial starts.

2. SUMMARY OF SCIENCE ACHIEVED

A. Gregg

i) By comparing observations of finescale shear and of ϵ (the turbulent dissipation rate) at different times and places, we found that averages of ϵ vary with the intensity of the shear. When internal waves dominate the shear, averages of ϵ agree within a factor of two with theoretical predictions of the rate of energy transferred to small scales by interactions within the internal wave field. If confirmed by further measurements, this agreement indicates that the predictions of wave-wave interactions give a first-order description of internal wave dynamics and provide a parameterization of turbulence in terms of the statistics of the internal wave field.

ii) Based on the results above, we obtained 20 expendable current profilers (XCPs) from NSF and dropped them in Santa Monica Basin. High vertical diffusivity in the basin had been inferred from the vertical thickening of tracer streaks injected by Ledwell. We analyzed the XCPs with URI funds and found shears much more intense than those parameterized in the Garrett and Munk spectrum and fully consistent with high vertical diffusivities.

Following the same approach to inferences of high diffusivities in the Antarctic Circumpolar Current, we dropped XCPs during Trevor McDougall's cruise in March 1991. These are being analyzed under the URI.

iii) Using high-frequency acoustic backscatter equipment (purchased on the URI), we imaged 15 m overturns in local water (Admiralty Inlet) while collecting profiles of density, shear, and ϵ. Unlike observations in the open ocean, these show the evolution of the overturn and the homogenization of the water column. Understanding this relation was a key objective of the URI. The observations also permit a quantitative comparison of microstructure with the backscatter cross section.

B. Rhines

Bottom boundary layer: MacCready and Rhines (1991a,b). We have developed laboratory experiments, numerical models, and theory that show the ocean's bottom boundary to be much "slipperier" than had been believed. The classic Ekman layer, long assumed to represent the correct physics of this region, is found to exist only on unusually flat bottoms, or for short duration. Buoyancy forces cause the boundary layer transport to shut down after $(f/N\alpha)$ half-pendulum days; after this, very slow diffusive processes provide the only momentum exchange with the interior. Here f is the Coriolis frequency, N the buoyancy frequency, and α the bottom slope. Our time-dependent picture sheds light on the idea of "boundary mixing" of the ocean, which previously was studied through statistically steady balances, and without momentum dynamics.

Oceanic boundary conditions and angular momentum balance: Rhines and MacCready (1989), Holloway and Rhines (1991). The local-vertical component of angular momentum is an interesting quantity that describes the

"spin" of the ocean circulation. Sources and sinks are provided by wind and lateral/bottom boundary. We discuss the way in which the boundary conditions assumed in ocean models impact this balance, which can sometimes be very paradoxical.

T-S finestructure and the mixing of deep water masses: Rhines, in preparation, 1991. CTD data from the SAVE cruises in the South Atlantic show interesting finestructure at the top of the North Atlantic Deep Water, in a layer about 1000 m thick, extending some 1000 km seaward from the western boundary. Enough is known about the slow movement of this water mass that its gradual erosion by mixing can be assessed. The generation of interleaving in this large region is unexpected, and its origin may be related to the local temperature inversion caused by cold, fresh Antarctic Intermediate Water just above.

C. Riley

We have addressed the problem of dynamic instabilities leading to turbulence and small-scale mixing in the ocean. Mainly stability theory and direct numerical simulations have been utilized in this work. We first addressed shear layer (Kelvin-Helmholtz) instabilities, and more recently have been examining internal wave breaking and the generation of turbulence. When the local Richardson number of a laminar shear layer is positive but low enough (well below 1/4), the flow transitions to turbulence, first through the appearance of two-dimensional vortices oriented in the cross-stream direction, then streamwise vortices, and finally turbulence. On the other hand, when the Richardson number is below but near 1/4, the flow breaks down, but the ensuing turbulence is much weaker. We have performed numerical simulations of such flows and calculated the ultimate amount of background mixing for different initial Richardson numbers. Internal wave propagation also leads to regions of strong shear, creating potential conditions for turbulence. But the possibility also exists for overturning motions, and the buoyant generation of turbulence. We have performed stability analyses and direct numerical simulations for these flows as well, for a range of wave amplitudes. For smaller wave amplitudes, shear instabilities similar to Kelvin-Helmholtz instabilities appear to be the dominant mechanism for transition to turbulence. For larger wave amplitudes, however, buoyantly driven instabilities

are more prevalent, resulting in the generation of streamwise vortices and then turbulence.

A useful tool for studying these phenomena is the energy balance of the flow. For example, for a shear layer undergoing transition to turbulence, the flow energy is initially almost entirely in the form of mean flow kinetic energy. As the instability develops, the mean flow kinetic energy is converted into fluctuating kinetic energy and then into potential energy. The potential energy is a result of moving fluid vertically against the buoyancy forces. Under some conditions, this potential energy can be converted back into kinetic energy, as the fluid is restored to its rest position under the influence of buoyancy forces. Diffusion, or molecular mixing, will inhibit the fluid from reacting to buoyancy forces and hence can make the potential energy unavailable for conversion back into kinetic energy.

To perform an energy balance on our simulated flow, it is thus necessary to measure not only the total potential energy but also that portion of the potential energy that is available for conversion to kinetic energy. We have developed an algorithm for measuring the total and available potential energy of a simulated flow field, and thus we can now perform a complete energy balance on the stably stratified flow simulations. This has been very useful for the analysis of our simulation results, and it has allowed, for example, the measurement of background mixing (i.e., the change in the background potential energy).

D. Sanford

Under URI support, analysis of observations in a subsurface eddy in the Gulf of Cadiz, a so-called Meddy, was undertaken. Such an eddy is a prominent example of the interaction of spatial scales. The Meddy clearly stems from the interaction of large-scale flow, evolves into a mesoscale feature, and dies through relentless small-scale mixing and dissipation.

An example of the scale interactions is shown by the vertical polarization of the velocity field as a function of position in the Meddy. Our analysis clearly shows that internal wave characteristics change markedly around this mesoscale feature. The changes are correlated with vorticity within the core, high velocity region, and outer flanks. These results are interpreted as evi-

dence of the generation of internal waves within the Meddy's core and of the interaction of these internal waves with the Meddy's vorticity, especially the vertical variation.

E. Van Atta

i) Discovered through a series of experiments with different fluids, different kinds of apparatus (water and wind tunnels, water tow tanks), and different initial conditions that the events characterizing the onset of buoyancy effects, collapse of turbulence, and restratification are universal and essentially independent of the generating mechanism.

Produced quantitative criteria which have been applied in the interpretation of the dynamics of mixing inferred from ocean microstructure measurements, including criteria for the existence of turbulent mixing and estimates of the buoyancy flux, which cannot be measured with present oceanographic instrumentation.

ii) Cospectral buoyancy flux measurements show that, during restratification events, active turbulent mixing occurs at the small scales simultaneously with counter-gradient flux at the large scales. Wavelet analysis of restratification process data confirms this scenario and provides a local measure of the relative strengths of the two physically distinct mixing processes.

iii) Quantitative measures of the growth rates and decay of turbulence and mixing were obtained for stably stratified shear flows. It was found that ratios of the Ozmidov scale to the density overturning scale reach an asymptotic value dependent only on the Richardson number. Reynolds and Froude number scalings and physical behavior were found to be similar to those observed in the recent thermocline measurements made from the research submarine *Dolphin*.

iv) Discovered that normalized buoyancy flux and related mixing efficiencies can have strong dependence on Schmidt or Prandtl number of the stratifying scalar. Obtained quantitative data to cover possible range of variance for ocean measurements.

v) Discovered a strong anisotropizing effect of buoyancy forces on the smallest scales of the turbulent velocity and density fields. Found that the

surprisingly rapid onset of anisotropy is both qualitatively and quantitatively in agreement with results of direct numerical simulation, but the effect was overlooked by the simulators. The large anisotropy in different components of the density gradient shows that the accuracy of the Osborn-Cox approximation for estimating fluxes depends strongly on the local value of the Brunt-Väisälä frequency.

F. Gregg and Sanford

i) Using data from past cruises, we constructed shear spectra spanning 0.01 to 100 cycles per meter (cpm). These are the first such spectra obtained from a single instrument, and they provide a more exact definition of spectral shape than available before. For wavenumbers less than 0.1 cpm, shapes are irregular when the intensities depart from the background state modeled by Garrett and Munk. At higher wavenumbers, however, spectra at mid-latitude have a universal shape, with a -1 roll-off until internal wave shear gives way to turbulent shear and the universal turbulence spectrum. At low latitudes, the spectra roll off more steeply than -1, indicating a change in dynamics of the internal wave field.

ii) Using partial support from the URI, in June 1990 we made the first observations of shear and turbulence in the Florida Strait. The data are still being analyzed, but show several regimes. Thick, turbulent boundary layers are found near the bottom across the strait. Outside these, internal waves seem dominant in the eastern part of the strait, and the ϵ scaling based on shear works well. On the west side, the additional shear of the Gulf Stream raises ϵ above the levels expected for production only by internal waves. We are using these observations to test parameterizations developed separately from regimes dominated by mean shear and by internal waves.

3. MAJOR FACILITIES DEVELOPED

A. Gregg

We purchased a BioSonics system for imaging high-frequency backscatter and developed it while working in Puget Sound. We now have real-time

color display on a MacII and have learned how to optimize the signal. The unit was used during the URI cruise to the Florida Strait and is also being employed on an NSF-funded cruise to the equatorial Pacific.

B. Rhines

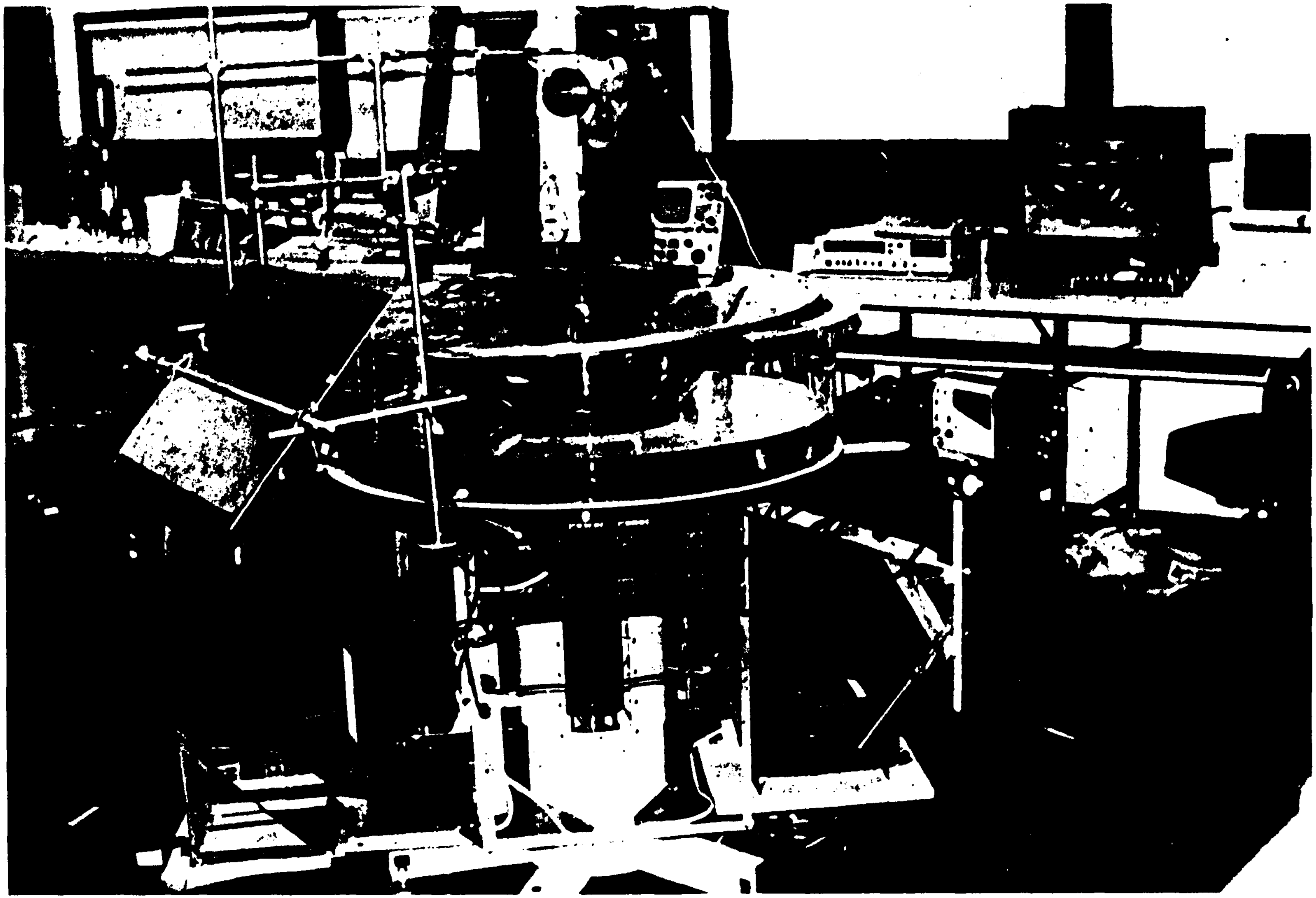
A new bottom proximity release was developed for MSP for the Florida Current experiment. Previously, MSP was not deployed in water shallower than its maximum working depth of 1100 m. The Florida Current operations required the development of a device to detect when the MSP was near the bottom and then to fire the weight-release mechanism. An acoustic proximity release was developed for this purpose and performed well during our recent MSP profiling.

The URI funding, together with a small direct grant from ONR, and an ONR OSEA postdoctoral fellowship grant, made possible the initiation of a Geophysical Fluid Dynamics (GFD) laboratory at the University of Washington. This lab functions both for research programs and teaching. There are currently 3 thesis students and 3 postdocs working there; 21 students have completed 10-week research projects since its inception in March of 1990.

The Geophysical Fluid Dynamics Laboratory runs two large rotating tables. A precision 1-meter table built with ONR funding (part from URI, part from a separate $40K grant) has a direct-drive dc motor with computer-controlled feedback circuitry. It is the platform for studies in rotating convection, wave-mean flow interaction, benthic boundary layers, and general circulation.

Measurements are made using a computer-controlled micro-CTD profiler and high-resolution time-lapse video cameras and a 35 mm camera mounted on the table. A vertical-horizontal traverse using stepper motors can carry probes on a preprogrammed measurement path throughout the fluid experiment. Multiplexed thermistor/conductivity chains are used to take swaths of data. For future work, a profiling two-axis laser-Doppler velocimeter is being tested, which may give us complete velocity sections down to a threshold speed of 0.2 mm s^{-1}.

We force the fluids using thermal boundary conditions (in one case, a



University of Washington School of Oceanography Geophysical Fluid Dynamics (GFD) Laboratory.

solid-state array of thermoelectric heating/cooling plates controlled by computer), and salt-fresh buoyancy flux (by injecting fluid into the tank through porous foams and membranes), as well as "tidal" forcing (programming the rotating table to oscillate its rotation rate), wind-stress (by moving plates and wind fans), and magnetic-tidal forcing.

We carry out experiments in a variety of "ocean-basin" geometries. We have found a fabricator who produces for us bowl-shaped Plexiglas tanks, as well as annular and cylindrical tanks.

C. Van Atta

i) Two-layer stably stratified shear layer facilities

Our first two-layer stably stratified shear layer facility is now in operation. Based on our early results we are constructing a second facility, with a wider test section, which will be run from the same supply reservoirs.

ii) Continuous gradient stratified shear layer

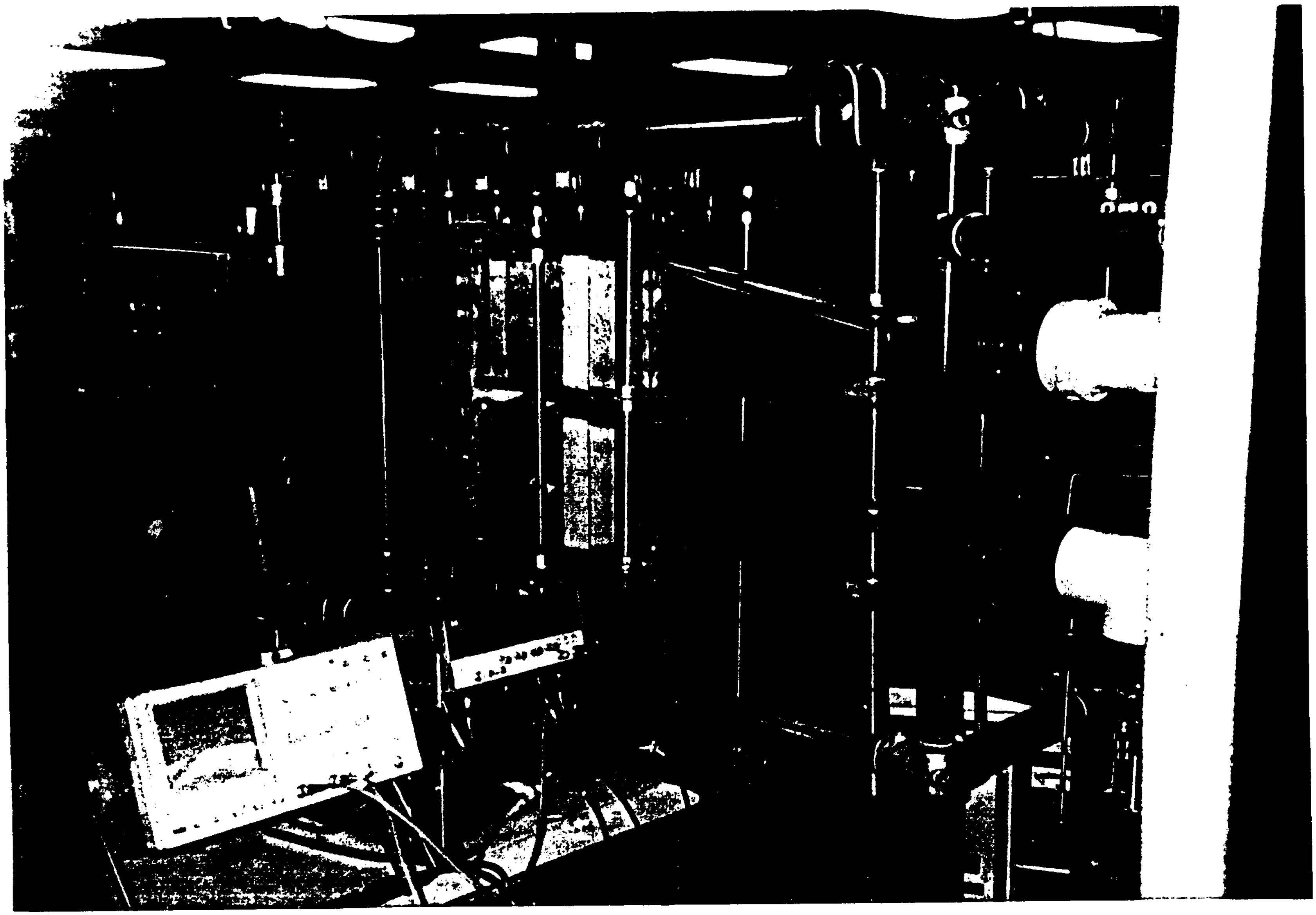
Prototypes for a continuous gradient facility using ten independent supply layers are being designed and tested. It will replace the original facility used in the first two years of the URI.

4. FUTURE DIRECTIONS ENABLED

A. Gregg

Parameterizations developed for ϵ in terms of internal wave shear give us an inexpensive tool for testing regions where high mixing is predicted. We have used it twice—Santa Monica Basin and the Antarctic Circumpolar Current—and will use it extensively in the future.

Acoustic imaging of large overturns lets us study the mechanisms and evolution of mixing, information badly needed to relate field observations to laboratory and numerical studies. This would not have been possible without the BioSonics backscatter unit purchased on the URI and without



"Stratified Shear Layer Facility" at UCSD, developed by Charles Van Atta.

the analysis done by Harvey Seim. We are preparing a proposal to NSF for more extensive measurements.

B. Rhines

The GFD laboratory is making possible a wide range of new research. We are currently working on ocean convection, simulating the modes of mesoscale and basin-scale circulation that occur when the sea surface is "densified" by cooling or evaporative salinity increase. We have developed a number of computer-controlled instruments following the major construction project of the precision rotating table.

To date we have had 21 students carry out one-term projects in the lab. They have produced many new results, which are beginning to appear in theses and even in journals. Dedicated thesis projects include

- Dan Codiga (M.Sc.) - Oscillation modes for seamount trapped waves
- Parker MacCready (Ph.D.) - Benthic boundary layers and oceanic spin-up.
- David Pierce - Rotating convection.

We currently have two postdoctoral investigators in the lab: Scott Condie (a UCAR Fellow) doing rotating convection and basin-scale circulation, and Dan Ohlsen (an OSEA Fellow funded by Rhines' ONR award) doing wave-mean flow interaction and β-effect simulations using ferromagnetic fluid.

C. Riley

This work has impacted other research and has also resulted in the initiation of new research. For example, the methodology developed to measure available and background potential energy is now being used by others who are performing simulations of stably stratified internal-wave and turbulent flows (e.g., Winters and D'Asaro). Diagnosing the energetics of such flows is important in their understanding, and our method is the only one presently available for their work. Our simulations of turbulence and wave breaking

University of Washington
School of Oceanography
graduate students in
GFD Lab.

have led to recently initiated work by the principal investigator (J.J. Riley) on turbulent boundary layer flow and on wave reflection and breaking over sloping terrain.

D. Sanford

The Meddy studies have confirmed our expectations of scale interactions. The scientific results will influence the direction of our internal wave research. For instance, we know that it is inappropriate to characterize deep ocean internal waves without taking into account the influences of mesoscale variability. We now appreciate how subthermocline eddies represent a laboratory in which scale interactions can be viewed in a quasi-steady setting. Theory and numerical modeling can be applied to the observations with higher expectations of success than in many natural situations.

Our operational capability, especially in MSP, and new knowledge will also let us undertake near-bottom projects, such as mixing in enclosed, shallow basins. In particular, we are following the URI-supported Rhines and MacCready into stratified flows on sloping bottoms with an ambitious observational program off the Blake-Bahama Outer Ridge in 1992. The URI studies have provided a strong scientific basis for the field program.

It is our plan to promote future internal wave observations and modeling which take the mesoscale interactions into account.

E. Van Atta

URI first-year equipment funding allowed us to develop and use nonintrusive optical techniques for single-point velocity and density measurements in stratified flows using LDA and LIF, two-dimensional full-field density measurements with LIF, and three-dimensional particle tracking with fluorescent particles. This new experimental ability has made a major impact on our research directions under the URI and on closely related work done under NSF Oceanography sponsorship.

The URI facilitated an exchange of ideas and information between physical oceanographers in several oceanographic institutions and in ONR, and our students and faculty doing basic laboratory studies. That interaction resulted in wider application of basic principles in interpreting ocean data.

This success and positive feedback encouraged us to submit a proposal to ONR for continued funding of our laboratory work at UCSC. This proposal, which was selected for funding at the recent SIO ONR site visit, would not have been possible without the earlier work supported by URI.

The impact of our laboratory experiments on interpretation of ocean microstructure measurements has been significant. Our results have already been used in the interpretation of ocean measurements and in theoretical studies published in the current oceanographic literature. A number of other applications of data obtained in more recent ocean studies and in related theory are in press, under review, or in progress.

The breadth of this response indicates that physical oceanographers are finding the laboratory results useful for guidance in physical interpretations of what they can measure, and that they are finding valuable insights in the results of idealized laboratory experiments.

5. SUMMARY AND LESSONS LEARNED

We have learned that extended interactions with investigators having diverse approaches greatly increases our scientific results. We have made a good start in tackling common problems across subdisciplines. We could have done a much better job of integrating our diverse approaches if we had had more time to plan the program—it was a crash program to develop the proposal—and if we had more budget continuity. Because of Gramm-Rudman and cuts imposed by ONR, we could not plan each year's work until we were into the year. As a result, we lost the ability to involve more investigators as collaborators.

APPENDIX A - FACULTY

Principal Investigators

Michael C. Gregg received a Ph.D. in oceanography from the University of California, San Diego, in 1971. He has concentrated on measuring turbulence in the ocean and on the relation of turbulence to the larger-scale processes producing it. An AGU Fellow and professor in the School of Oceanography, Gregg also is on the staff of the Applied Physics Laboratory at the University of Washington.

Peter B. Rhines received his Ph.D. from Cambridge University (Cambridge, England) in 1967. He is a Professor of Oceanography and a Professor of Atmospheric Sciences at the University of Washington, a Senior Fellow at JISAO, a member of the National Academy of Sciences, and an AGU Fellow. His research interests include the general circulation of the oceans, geophysical fluid dynamics, theory of waves and large-scale turbulence in oceans and atmospheres, computer modeling of circulation, wave-mean flow interaction, and trace chemistry and its interaction with climate.

James J. Riley received his Ph.D. in Mechanical Engineering from Johns Hopkins University in 1971. His research includes the study of direct numerical simulations of stably stratified fluid flow, particularly the development of turbulence in the presence of density stratification. He teaches undergraduate an graduate courses in fluid mechanics, turbulence, and fluid stability in the Mechanical Engineering Department at the University of Washington. He also holds an adjunct appointment in the Department of Applied Mathematics.

Thomas B. Sanford received his Ph.D. in Oceanography and Mathematics from the Massachusetts Institute of Technology in 1967. From there he went to the Woods Hole Oceanographic Institution as a scientist and then to the University of Washington where he is a Professor of Oceanography and a Principal Oceanographer in the Applied Physics Laboratory. Dr. Sanford's research interests include the measurement and interpretation of motionally induced electric and magnetic fields in the sea and within channels; structure and dynamics of ocean currents, eddies, and waves; generation, propagation, and dissipation of internal waves and microstructure; magnetotelluric studies

in the deep sea; and development of oceanographic sensors and instrumentation. Dr. Sanford contributed his insights and observations in the areas of mesoscale and finescale variability. He was Co-PI in the Florida Current experiment of June 1990 and serves as supervisor for Mark Prater, UW graduate student.

Charles W. Van Atta received his Ph.D. in Aeronautics/Fluid Mechanics from the California Institute of Technology in 1965. He is a Professor of Engineering Physics and Oceanography in the Departments of Applied Mechanics and Engineering Sciences at Scripps Institution of Oceanography. His research interests include geophysical fluid dynamics, especially turbulent flows; laboratory and field studies of flow structure; spectral energy transfer; influences of stratification and rotation; and statistical and determinate models for fluid flows.

Visits and Collaborators

Christopher Garrett received his Ph.D. in Fluid Mechanics from Cambridge University in 1968. Following postdoctoral studies with Robert Steward (University of British Columbia) and Walter Munk (University of California, San Diego), he has worked on theoretical problems of oceanography. Small-scale mixing has been a continuing theme in these studies.

Ross Griffiths, a Principal Scientific Officer at the Research School for Earth Sciences, Australia National University, received his Ph.D. from Cambridge University. He specializes in fluid convection processes and laboratory experimental techniques. He provided us detailed design drawings for our rotating table, which we modified for use in the Geophysical Fluid Dynamics Laboratory. Certain special aluminum castings for the table were cast in Australia under his supervision and shipped to us. Beyond this, Griffiths provided a wide range of insights during his visit to Seattle, ranging from laboratory techniques to rotating convection dynamics.

Eric Kunze received his Ph.D. in Physical Oceanography from the University of Washington in 1985. Following postdoctoral work at Woods Hole Oceanographic Institution, Dr. Kunze accepted a research/teaching position in the School of Oceanography at the University of Washington. He is making significant contributions to the understanding of double diffusivity, inertial

wave interactions with geostrophic fronts, and divergence and vorticity of the finestructure velocity field.

Trevor MacDougall, a Principal Scientific Officer at CSIRO Oceanography Laboratory, Hobart, Tasmania, Australia, received his Ph.D. from Cambridge University. McDougall is the singular expert on ocean convection and mixing processes which involve the true equation of state of seawater. His new formulations of diapycnal flow and mixing lay the groundwork for understanding such diverse phenomena as cabbeling, double diffusion, thermobaric convection, aspects of ocean-boundary mixing, and diapycnal density transport. These ideas are crucial to incorporating mixing in the next generation of oceanic general circulation models.

APPENDIX B - STUDENTS SUPPORTED

Dr. Todd Barrett, with partial support from URI funding, received his Ph.D. (Engineering Sciences, Applied Mechanics) from UCSD in 1989. His thesis title was "Nonintrusive optical measurements of turbulence and mixing in a stably stratified fluid." Dr. Barrett is currently at Thermo-Electron Corp., working on SDI projects.

Laura Landrum, supported 100% by the URI, received her M.S. degree studying the interaction of baroclinic eddies with transport of tracers and potential vorticity. She is currently working with chemists on modeling the upper ocean for climate under a NASA Global Change Fellowship and pursuing her Ph.D. in Chemical Oceanography.

Dr. John Lienhard V studied with Dr. Charles Van Atta at UCSD and received his Ph.D. (Engineering Sciences, Applied Mechanics) in 1988 while receiving partial support from URI funds. He is currently a professor at MIT.

Peter N. Lombard completed his Master of Science in Mechanical Engineering at the University of Washington, studying numerical simulations of stably stratified turbulent flows. He is continuing to work with James Riley toward a Ph.D. in Mechanical Engineering, investigating the stability of finite amplitude internal gravity waves. Although slowly growing two-dimensional instabilities have been identified in internal gravity waves, it appears that a three-dimensional instability may lead to the collapse of internal waves into turbulence in both the ocean and the atmosphere.

Parker MacCready, supported 50% by the URI, completed his Ph.D. in June 1991—a study of the oceanic bottom boundary layer. Currently employed in the GFD laboratory, he will assume a postdoctoral fellowship at the Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, in October 1991.

Paul Piccirillo, Chee Yap, and David Schowalter have received partial support from URI, and each has approximately 2 years to go to receive Ph.D.'s at UCSD, all studying turbulent mixing in stratified fluids.

Mark D. Prater is supported under this URI and is expected to defend his dissertation this fall. His research is on the generation and structure of a Meddy. He has shown that the Meddy was formed in the submarine canyon region off the southern Portuguese coast and has evaluated possible formation mechanisms. The structure of the Meddy is described in terms of temperature, salinity, and velocity. The balance of terms and dynamical considerations are extensively pursued in the dissertation. He expects to seek employment at the Naval Underwater Systems Center or the University of Rhode Island.

Harvey Seim received full support from the URI and will receive his Ph.D. in 1992. He works with Dr. Michael Gregg and is analyzing large turbulent overturns observed in Admiralty Inlet to relate the turbulent intensity to changes in potential energy of the stratification. He is also comparing thermal microstructure with simultaneous measurements of acoustic backscatter. Seim plans to do academic research after completing his degree.

Siggurdur Thoroddsen, who has been partially supported with URI funds, is studying turbulent mixing in stratified fluids with Dr. Van Atta at UCSD, and is expected to receive his Ph.D. within the year.

Matt Trunnell, current second year graduate student (jointly supported with NSF), is working on chemical/physical oceanographic interactions.

APPENDIX C - PUBLICATIONS

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APPENDIX D - NAVY AND DOD INTERACTIONS

We had repeated meetings with scientists from the numerical modeling group at NORDA, but no useful collaboration was obtained. There were no other interactions.